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National Nuclear Security Administration's
Lawrence Livermore National Laboratory


## National Ignition Facility Comes to Life

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# The National Ignition Facility Comes to Life

*Successful commissioning shows that scientific vision, technical innovation, a talented team, and sheer hard work prevail.*

"NIF-scale" runs the gamut from its facility the size of a football stadium with 192 beamlines (background) leading to a target held inside the hohlraum ignition target (foreground).

FIRST conceived of nearly 15 years ago, the National Ignition Facility (NIF) is up and running and successful beyond almost everyone's expectations. During commissioning of the first four laser beams, the laser system met design specifications for everything from beam quality to energy output. NIF will eventually have 192 laser beams. Yet with just 2 percent of its final beam configuration complete, NIF has already produced the highest energy laser shots in the world.

In July, laser shots in the infrared wavelength using four beams produced a total of 26.5 kilojoules of energy per beam, not only meeting NIF's design energy requirement of 20 kilojoules per beam but also exceeding the energy of any other infrared laser beamline. In another campaign, NIF produced over 11.4 kilojoules of energy when the infrared light was converted to green light. And an earlier performance campaign of laser light that had been frequency converted from infrared to ultraviolet really proved NIF's mettle. Over 10.4 kilojoules of ultraviolet energy were produced in about 4 billionths of a second. If all 192 beamlines were to operate at these levels, over 2 megajoules of energy would result. That much energy for the pulse duration of several nanoseconds is about 500 trillion watts of power, more than 500 times the U.S. peak generating power.

And how will that vast energy and power be used? Scientists interested in the behavior of materials at high temperatures and pressures will be able to explore entirely new states of matter and generate accurate data at extreme pressure . NIF can create temperatures—tens of millions of degrees—similar to those inside the Sun and stars. NIF's carefully controlled pulses can also drive experiments to pressures never before seen in a laboratory setting. NIF will achieve pressures higher than a billion times atmospheric pressure, which is over a million times the pressure at the deepest part of the oceans and equivalent to pressures at the center of the Sun. Some of the earliest experiments are designed to examine how various materials fail and demonstrate the behavior of planetary fluids such as those found inside Jupiter.

The sheer magnitude of the National Nuclear Security Administration's (NNSA's) $3.448-billion NIF is staggering. The building is the size of a football stadium, nearly 26,500 square meters and 10 stories high, with several adjacent support facilities. All that space is chock full. Commissioning Manager Bruno Van Wonterghem comments that this project has tested the limits of how much high-tech equipment can be squeezed into a given space.

The laser system is composed of more than 3,000 40-kilogram slabs of laser glass, 26,000 smaller glass optics, 3,000 laser mirrors and lenses, and over 1,000 crystalline optics (see the figure on p. 6). More than 7,600 of the largest flashlamps ever built, each of them 2 meters long, power the laser system. When the full constellation of beams is operating in 2008, NIF will deliver more than 50 times the energy of Livermore's Nova laser, decommissioned in 1999, or the Omega laser at the University of Rochester Laboratory for Laser Energetics.

"But the most important thing about NIF," says Ed Moses, NIF project manager since 1999, " is not the parts count. It's how NIF is designed and integrated. Designing and commissioning any large project demands a systems approach. Putting together NIF's many systems has been like playing chess against a grand master. You can't win if you only look one move ahead at a small part of the board. We've had to look at the whole effort all at once and as far ahead as possible." Moses is quick to credit physicist Mary Spaeth, NIF's chief technical officer, and her systems engineering team for delivering a fully integrated and flexible target-shooting system as well as Ralph Patterson, NIF's chief operations officer, for managing the budget and schedule strategy.

## Built-In Flexibility

Unprecedented flexibility has been designed into NIF to maximize its experimental capabilities. Changing the laser's energy or pulse shape is easy. Ultraclean modular optical systems simply plug in all along the beampath and can easily be removed for maintenance or upgrade. Diagnostic equipment at the target chamber is also designed for "plug-and-play" operation.

The activation of the first four beams, known as a quad, took place a year earlier than originally planned. This campaign, known as NIF Early Light, was designed to demonstrate NIF's capability to deliver high-quality energetic laser beams in support of experiments. Also, notes Co-Commissioning Operations Manager Gina Bonanno, "By validating virtually all representative parts of NIF with that first quad, we were able to untangle some unforeseen snags. We think that the rest of the beam commissioning can proceed smoothly,"

Moses adds, "Because each NIF bundle—an upper and lower quad—is essentially independent from the others, NIF will be operational while the installation of additional beams proceeds."

By June 2006, a total of 48 beams, a cluster, will be operational. After that,


(a)


(b)

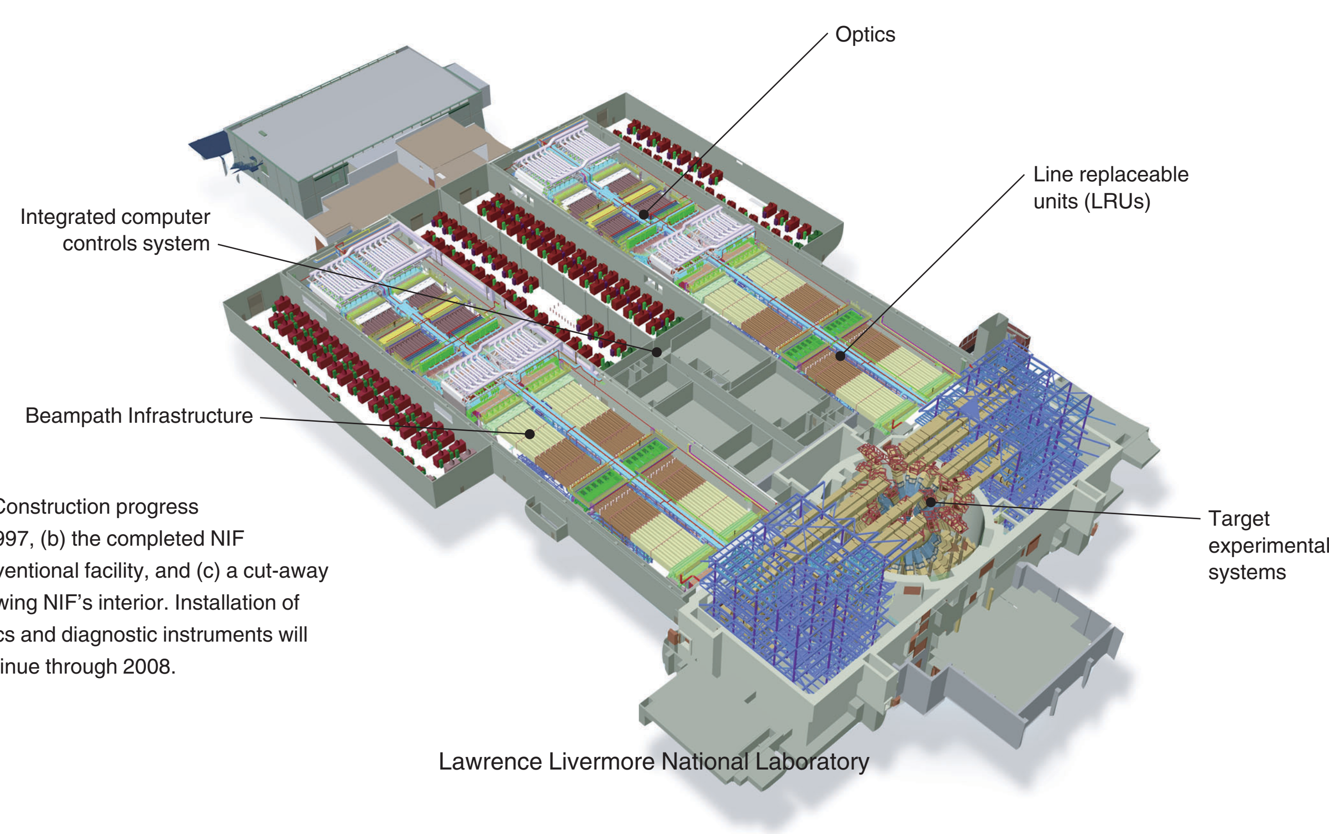
the other clusters will be installed and commissioned at a much faster rate.

NIF, a cornerstone of NNSA's Stockpile Stewardship Program, will provide assurances of the performance and reliability of the U.S. stockpile. Even with just a few beams operational, NIF will make significant contributions to astrophysics, hydrodynamics, material science, and plasma physics. By 2008, all 192 beams will be routinely firing in experiments that will create physical regimes never before seen in any laboratory setting—to benefit maintenance of the U.S. nuclear weapon stockpile, spur advances in fusion energy, and open up new vistas in basic science.

## Building Success

Thousands of Livermore engineers, scientists, and technicians have been involved in NIF over the last 15 years, first in proposing that such a massive laser might even be possible and later in designing the specialized equipment housed inside, much of it the first of its kind. Hundreds more construction personnel, employees of equipment suppliers, and testing and

(c)




(a) Construction progress in 1997, (b) the completed NIF conventional facility, and (c) a cut-away showing NIF's interior. Installation of optics and diagnostic instruments will continue through 2008.

commissioning experts have brought the NIF dream to reality.

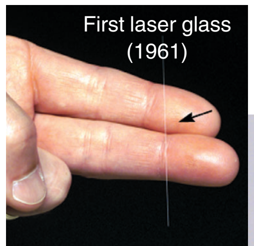
When Livermore broke ground for NIF's conventional facilities (the building and supporting infrastructure), Valerie Roberts was NIF's construction manager. Her team knew this phase of the project was the largest the Laboratory had ever attempted, and it had to be complete by the end of September 2001. But the construction schedule couldn't anticipate everything. In November 1997, El Niño rains flooded the NIF site. A month later, a backhoe uncovered the remains of a 16,000-year-old mammoth. Niffie, as local schoolchildren named him, had to be excavated by an archaeological team from the University of California at Berkeley.

Meanwhile, NIF's target chamber was being built. The spherical chamber is made from 6,800-kilogram, 10-centimeter-thick flat aluminum plates, each like a segment of a volleyball. The plates were cast in West Virginia, shaped in France, precision-edge machined in Pennsylvania, and then shipped to Livermore where they were fit together and welded. After assembly, 192 holes of various sizes were precisely located and bored for laser beams, diagnostic instruments, targets, and other equipment that will be put into the chamber. The completed chamber was hoisted onto a concrete pedestal inside the target building in June 1999.

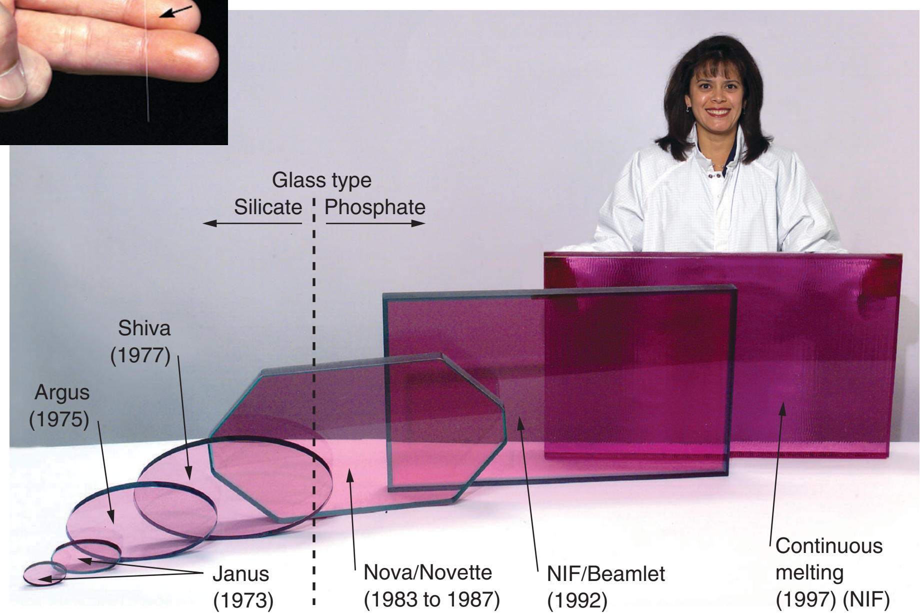
The chamber serves as an optical bench holding all frequency conversion and focusing optics. It is designed to withstand debris and neutron and gamma radiation from experiments and to maintain vacuum and cryogenic environments for experiments.

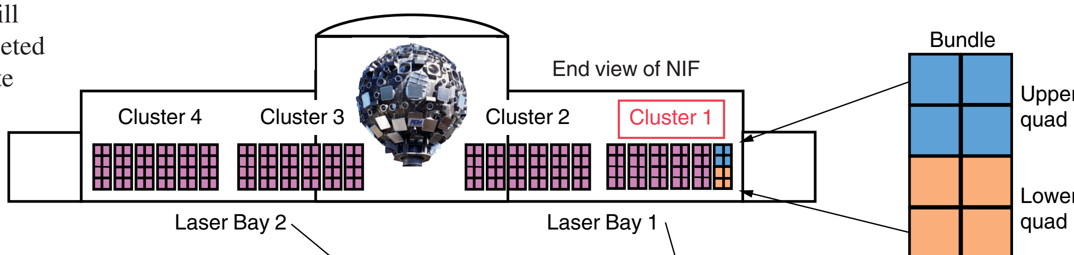
As the conventional facility took shape, the team developed a revised baseline plan to implement NIF Early Light. Its goal was to advance the activation of the first beamlines by over a year. Thus, before the building was complete, workers were already beginning to install the laser beampath.

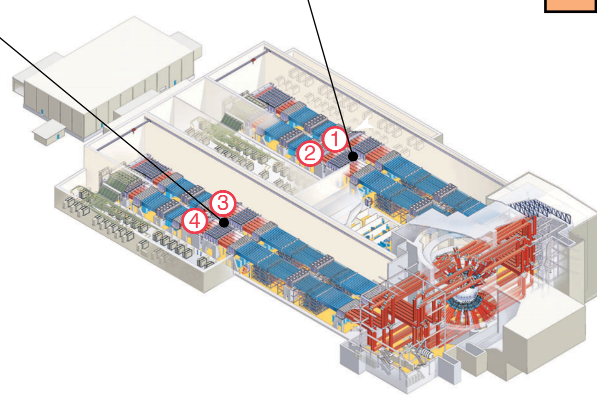
By the time construction of the conventional facility was completed in September 2001, the first modular line replaceable unit (LRU) had been installed and its cleanliness requirements measured and verified. Says Associate Project Manager Doug Larson, "The LRU engineering team designed over 20 different types of LRUs, successfully balancing cost with precision, stability, and cleanliness requirements. Although



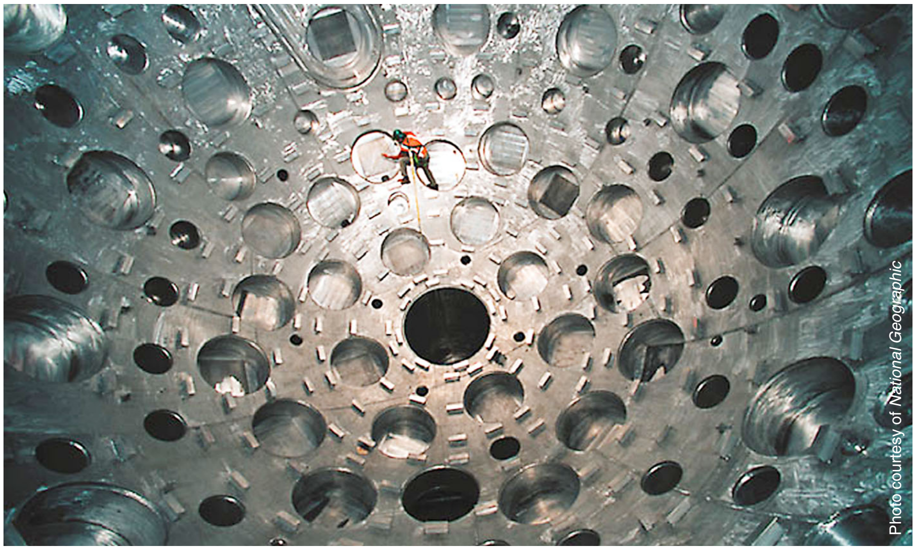

The slabs of laser glass needed in NIF's optics are the largest ever made. Laser glass technology has improved dramatically to meet the needs of NIF.




NIF's 192 beams are organized into bays, clusters, bundles, and quads. Quads (each group of four beams) are the basic building blocks of a NIF experiment, with each quad having the same pulse shape and time delay.




Inside NIF's 10-meter-diameter target chamber.

some assemblies are the size of a phone booth, all must repeatably position optical surfaces to within a fraction of a millimeter." (See the box on p. 10 for more information on LRUs and other laser technologies.) A month later, the master oscillator, which provides the low-energy seed laser pulse for NIF, generated its first light.

By August 2002, the first Laser Bay 2 beamline was successfully aligned using a light source propagated through an entire beamline. The alignment provided the first test of the integrated operation of laser controls, safety, and utilities systems. "While this accomplishment may appear simple, it was actually quite remarkable," says


In April 2003, the NIF team celebrated 3 million hours without a lost workday injury. By July, the number of hours had grown to 3.3 million.

## Why "Ignition" Is NIF's Middle Name

The idea for the National Ignition Facility (NIF) grew out of the decades-long effort to generate self-sustaining nuclear fusion reactions in the laboratory. Livermore's Director Emeritus John Nuckolls was among the first to conceive of the idea shortly after the laser was invented. Theorists, supported by years of experiments, have defined the conditions required to compress and heat a fuel of deuterium and tritium (isotopes of hydrogen) to temperatures and pressures that will ignite and burn the fuel to produce energy gain.

The energy and power of NIF's 192 beams will compress and heat a tiny fusion capsule to those extreme conditions. Unlocking the stored energy of atomic nuclei will produce approximately 10 times the amount of energy required to initiate the self-sustaining fusion burn. With ignition experiments, scientists can examine the conditions associated with the inner workings of exploding nuclear weapons, understand the processes that power the Sun and stars, and enhance our ability to eventually produce fusion energy for electrical power production.

Jeff Atherton, project manager for the beampath infrastructure system. “It validated the precision construction and surveys required to achieve NIF’s pointing accuracy over the length of its 300-meter beampath—which is like throwing a strike from Pac Bell Park in San Francisco to Dodger Stadium in Los Angeles.”

In September 2003, the construction team completed the three-year effort to build the beampath through which laser beams are transmitted, from the preamplifier system to the switchyard. Through these ultraclean enclosures, with their controlled temperature and humidity, 192 precision-aligned laser beams will eventually zoom to the switchyard in about 1-millionth of a second.

“Perhaps the most beautiful part of NIF is being built right now,” adds Chief Engineer Rick Sawicki, who has been part of the NIF team since 1993. The mirror frames that redirect the linear arrangement of laser beams to the center of the spherical target chamber are creating “a forest of shining silver beamlines coming through the floor and ceiling of the target bay.”

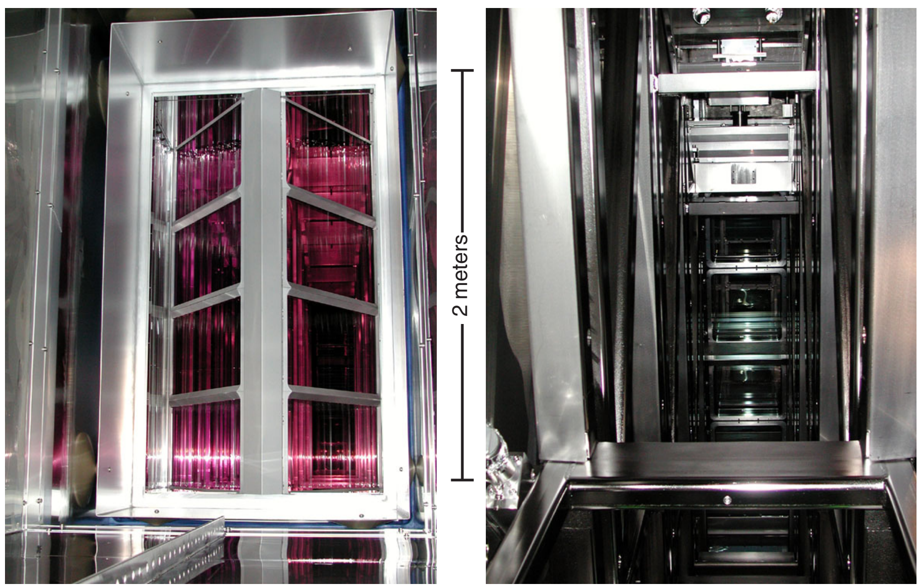
Throughout construction and commissioning, safety has been the number one priority. In July 2003, the construction team surpassed 3.3 million work hours in 950 consecutive days without any workdays lost to injuries. The National Safety Council honored NIF with Perfect Year awards for 2001 and 2002, and the project team received a Construction Industry Safety Excellence Award from the Construction Users Round Table. Site Manager Vaughn Draggoo, Site Safety Manager Arnie Clobes, and NIF Safety Integrator George Stalnaker are justifiably proud of this outstanding safety record accomplished in a complex work environment.

## Record-Setting Beam Quality

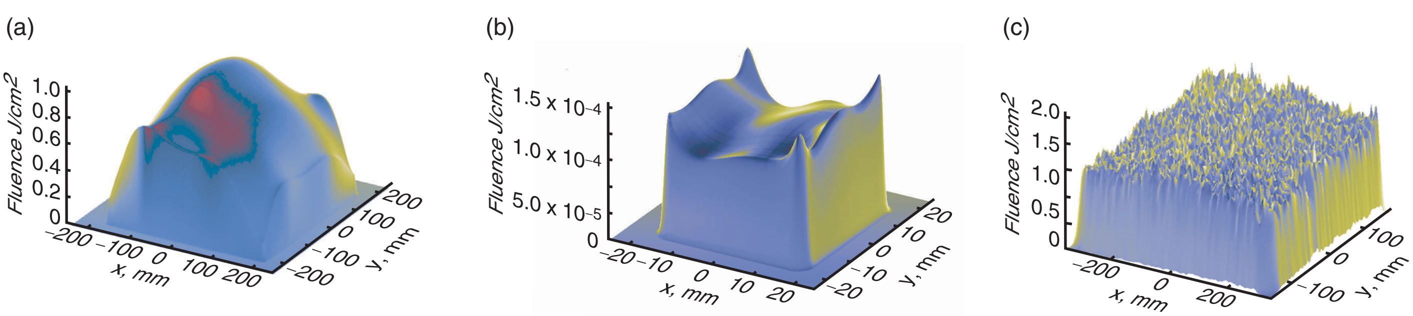
A key to NIF’s ultimate worth and ability to perform physics experiments is the quality of its laser light. To test and commission the laser, shot campaigns are carefully planned and modeled in advance.

In November 2002, commissioning teams completed a series of laser shots that verified the absence of parasitic oscillations within NIF’s main and power amplifiers. Parasitic oscillations are “renegade” light beams that divert from the main laser path. If present, they can degrade laser performance or even damage laser components. They can occur because of reflections all along the amplifiers’ “hall of mirrors.”

A few weeks later, in early December, the first amplified infrared laser light ran through Laser Bay 2 and




The interiors of NIF’s many laser components form a hall of mirrors. Parasitic oscillation paths that could degrade the laser’s performance have been mitigated.




Modeling that predicted (a) the gain profile (shape of the beam after amplification) was also used to design (b) a reciprocal intensity mask for the preamplifiers so the resulting beam would have uniform intensity. The result is shown in (c) an actual measurement of a NIF intensity profile.

into Switchyard 2. This 43-kilojoule shot in four beams exceeded a NIF milestone of 10 kilojoules of amplified light per beam. Long before that first quad of beams was fired, extensive scientific modeling had characterized almost every facet of its performance: the shape of the beam, the distortions collected as the beam travels through the amplification system, and the shape of the pulse.

Modeling results were used in the engineering efforts to perfect all aspects of the laser beam. For example, modeling predicted the gain profile, that is, the intensity of the beam front after it has been fully amplified. Because a uniform beam is essential, an intensity mask installed in the preamplifiers compensated for the anticipated gain profile. Similarly, the deformable mirrors (described below) compensate for predicted beam distortion and allow the beam's focal spot in the target chamber to be nearly perfect. Calculations also indicated the need for modifications that smooth the temporal shape of the beam.

In April, when the commissioning team ran the infrared shot campaign that produced 83 kilojoules, reaching this energy milestone requirement of 20 kilojoules per beam was not a

## The Technologies That Make NIF Possible

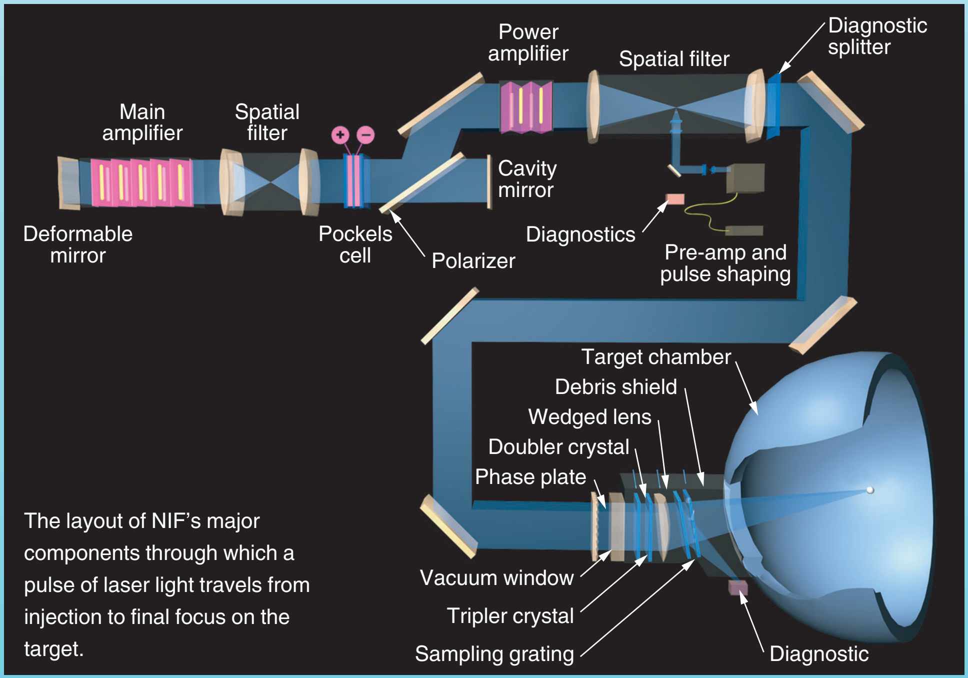
The National Ignition Facility's (NIF's) laser components shape and smooth the initial pulse, amplify it over a quadrillion times, and precisely direct it at a tiny target in the target chamber. Many components have required significant advances in laser technology, while others are entirely new. As subsystems were developed, most were tested on Beamlet, a scientific prototype that operated from 1994 to 1998. Project Manager Ed Moses refers to six of the laser's systems as the "six miracles of NIF," because without these breakthroughs, NIF would be far less capable or perhaps could not have been built at all.

The first miracle, at the beginning of the system, is the injection laser system. It makes the seed for the laser beams—a light pulse that contains all the spatial, temporal, and spectral information that the big laser glass systems amplify. All components of the injection laser system must operate in perfect harmony so that each quad of beams will have its specified energy and timing. The 48 injection laser systems are the most sophisticated lasers of their kind.

Next stop for the pulse is the main amplifier. For every bundle of eight beams, an amplifier module uses 128 slabs of neodymium-doped phosphate glass surrounded by flashlamps to amplify the beams many times over as they travel back and forth through the glass.

Amplifiers and other optical components have been made modular to reduce system downtime and enhance maintenance. Over the years, Livermore scientists learned of the need to maintain a clean environment around the path of the laser to avoid damaging the laser's optics and degrading the beam. The optical modules, known as line replaceable units (LRUs) are assembled in the Optics Assembly Building, a clean-room facility adjacent to the main building. Robotic assembly facilitates the handling of parts as heavy as 1,800 kilograms. LRUs are transported to the laser area via a portable clean room to maintain cleanliness all the way through installation and alignment. LRUs can easily be removed and refurbished or upgraded.

The neodymium-doped phosphate laser glass, the second miracle, is the result of a six-year joint research and development program with industrial partners Schott Glass Technologies and




The layout of NIF's major components through which a pulse of laser light travels from injection to final focus on the target.

surprise. By July, the team achieved energy of 26.5 kilojoules per beam, for a total of 106 kilojoules. Models predict that 30 kilojoules of infrared light per beam can be attained.

The result of this huge modeling and technology effort is the best beam quality ever demonstrated in a fusion-class laser system and the highest-energy infrared, green, and ultraviolet laser system operating anywhere in the world.

### Controlling It All

Commissioning Operations Managers Gina Bonanno and Steve Johnson are working with Van Wonterghem to assure the facility's success. "Making sure everything works and works together," is how Johnson sums up his job.

"Because of the size of the project and with so much going on at once, little things come up every day that have to be dealt with," adds Bonanno. "We are constantly evaluating priorities, deciding on trade-offs. Some part isn't going to be here on time. How do you work around this challenge?"

Physicist Ralph Speck, 75 years old and mostly retired, is assisting with NIF commissioning, too. He has been involved in the commissioning of almost all of Livermore's lasers since

Hoya Corporation. This effort, led by Associate Project Manager Jack Campbell, developed a revolutionary process for manufacturing meter-size slabs of laser glass that is 10 times faster, 5 times cheaper, and with better optical quality than previous batch processes. The team won an R&D 100 Award and a Lawrence Livermore Science and Technology Award for developing this process.

The next miracle is the plasma electrode Pockels cell (PEPC, pronounced like the soft drink) in the main amplification system. Each PEPC uses a thin slice of KDP (potassium dihydrogen phosphate) crystal measuring 40 by 40 centimeters and sandwiched between two gas-discharge plasmas. The plasmas are so tenuous that they have no effect on the laser beam passing through the cell, yet they serve as effective conducting electrodes. The PEPC is an optical switch, allowing the laser light to pass through the amplifiers four times. Says Moses, "As if NIF weren't big enough already, it would be almost 250 meters longer without the PEPC and probably could not have been built."

The fourth miracle was the development of technologies to quickly grow large, high-quality KDP crystals and to machine them to NIF's tight tolerances. KDP is used in the PEPCs to switch the polarization of the light and in the final optics to convert laser light from infrared to both green and ultraviolet light. About 600 large slices of KDP were needed, and growing big enough crystals by traditional methods would have taken years. A fast-growth method, pioneered in Russia and perfected at Livermore, produces crystal boules of the required size in just months. This team also won an R&D 100 Award. To machine and finish the crystal slices to NIF tolerances, the KDP crystal manufacturer is using methods developed by Livermore precision engineers.

As the NIF beams fly through the amplifiers, they accumulate wavefront aberrations from miniscule optical distortions in the amplifier glass and other materials. To compensate for the distortions, Livermore researchers developed a sort of "prescription lens," a 40-centimeter deformable (movable) mirror, another miracle. Each laser beamline incorporates a deformable mirror with 39 computer-controlled actuators on the back to adjust its surface. The mirror corrects distortions in the beam profile so that it can be focused to a submillimeter spot in the target chamber.

The sixth and final miracle is NIF's control system. "Without this system, NIF could not be the well-integrated system that it is," says Moses. As in all of NIF, flexibility is designed into the control system. After more than a decade of experience with Nova, Livermore designers know NIF will evolve over its projected 30-year lifetime.



(a) A KDP crystal for NIF's optical system and (b) a deformable mirror to eliminate wavefront aberrations in the laser beam.

Janus, and he led the commissioning of Nova in the early 1980s. Speck says, “The engineering on NIF is better than on any big laser I’ve ever worked on before—and I’ve worked on almost all of them.”

Today, laser shots for commissioning the laser and for the first physics experiments are running at up to three a day. None of them would be possible without NIF’s control system. According to Associate Project Manager Paul VanArsdall, the likes of the integrated computer control system have never before been seen on a laser. (See *S&TR*, November 1998, pp. 4–11.)

NIF’s control system will eventually handle the computerized monitoring and control of some 60,000 elements throughout the system, including safety interlocks, alignment systems, mirrors, lenses, motors, sensors, cameras, amplifiers, capacitors, and diagnostic instruments. Twenty-four hours a day, the system supervises shot setup and countdown; oversees machine interlocks to protect hardware, data, and personnel; generates reports on system performance; provides operators with graphical interfaces for control and system status displays; performs alignment, diagnosis, and control of power conditioning and electro-optic subsystems; and monitors the health of all subsystems and components.

### NIF’s Reason for Being

Exploring the world of high-energy-density physics is NIF’s entire reason for being. Using NIF’s unique capabilities, scientists will delve into the inner workings of nuclear weapons, astrophysical phenomena such as supernovae, and materials under extreme conditions.

Physicist Brian MacGowan is the program manager for NIF’s facility diagnostics that collect information during each experiment. He notes that because the first quad of beams is highly efficient in delivering energy to the target, NIF can create energetic laser pulses with the longest duration and most precisely tailored shape ever achieved on a large glass laser system. NIF also has the flexibility to generate a range of pulse shapes and durations with varying power and energy. Tailored pulses will be key for all experiments on NIF, providing the capability to drive materials and complex targets to states of high energy density.

Permanent facility diagnostics in NIF’s target area include x-ray imaging systems, high-speed framing cameras, and the largest-ever VISAR laser interferometer, which measures the velocity of shock waves. Eventually, as many as 40 diagnostic tools can be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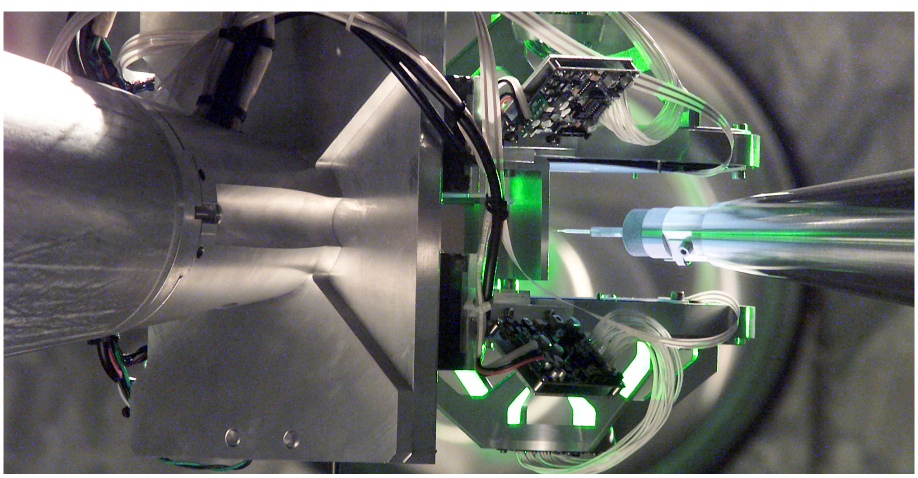


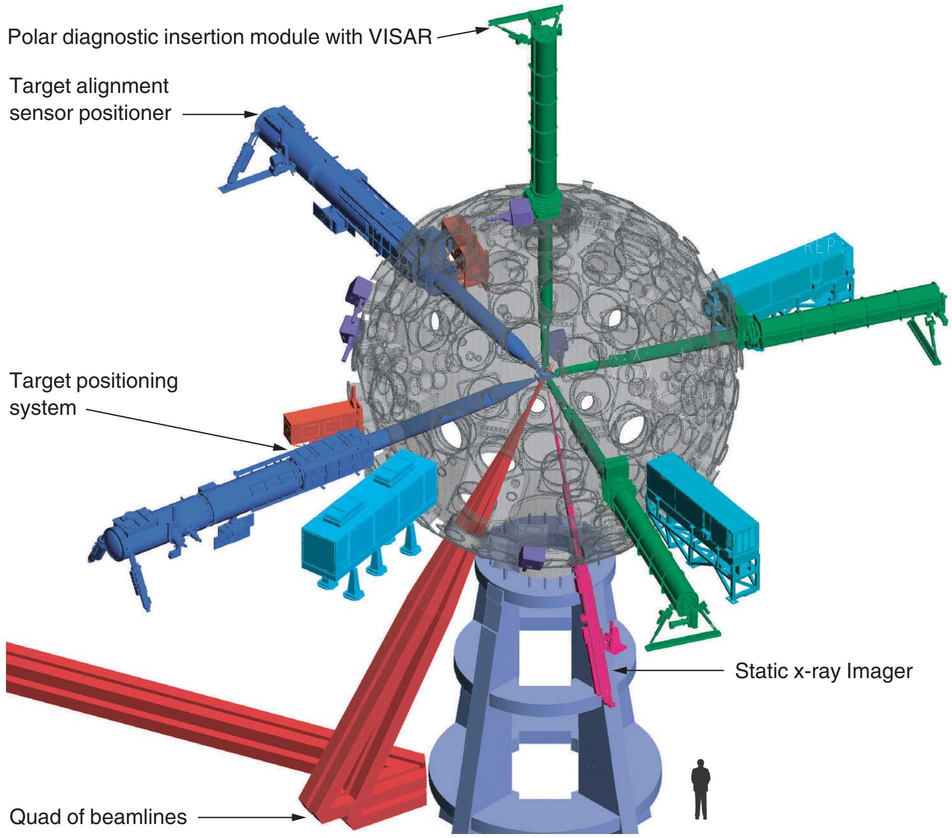
Inside the target chamber, the target alignment sensor positioner (at far left) is being used to align a tiny target, which would be at the tip of the target positioning system entering from the right. The green light illuminates objects within the chamber.

installed, either permanently or temporarily, on the target chamber. Also in place is the full-aperture backscatter detector under the target chamber. Characterizing the light backscattered from experiments provides information about laser–plasma interactions that is critical for future fusion experiments.

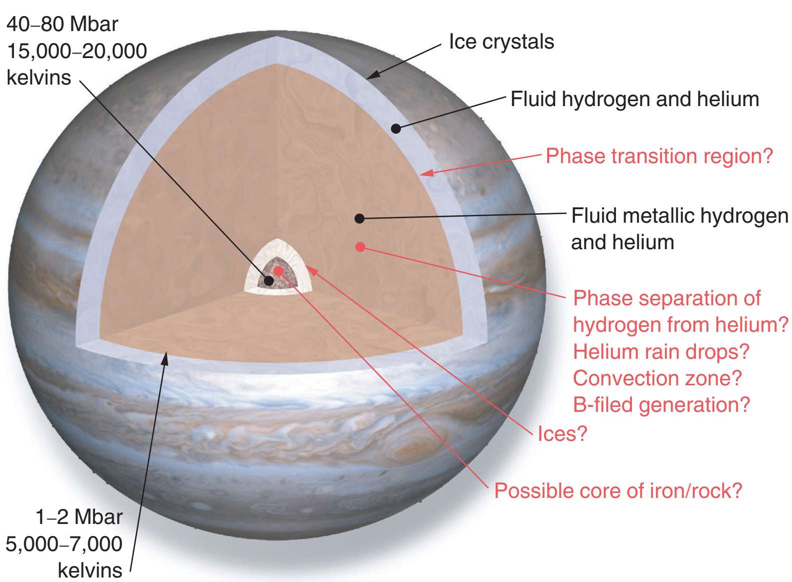
With NIF's tailored pulses, physicists can generate the longest lasting high-density plasmas ever produced. A set of early experiments will use special gas-filled targets, whimsically called gas bags, to produce large-scale plasmas that approach the conditions expected to be found in later gas-filled hohlraum fusion experiments.

Hydrodynamics—the behavior of fluids of unequal density as they mix—is an important issue for stockpile stewardship and for understanding the behavior of stellar evolution and supernovae. Weapons use solid materials, but solid materials driven to states of high energy density tend to behave as if they were fluids. The hydrodynamic behavior of mixtures of heavy and light materials is also key to understanding astrophysical phenomena such as supernovae. Even in the first hydrodynamic experiments using four beams, in which one beam backlights the experiment, the remaining three offer a major increase in capability over that available at other experimental facilities.

NIF-scale cryogenic ignition targets, known as hohlraums, are expected to be ready for use in 2006. When they are combined with more laser beams, increasingly sophisticated fusion experiments will begin. And when even more beams are firing on a target, NIF will approach the high temperatures seen inside exploding nuclear weapons. As ignition and higher-energy-density experiments become possible, additional diagnostics will be commissioned to detect neutrons,




The first quad of beams is shown entering the target chamber. Thus far, four instruments mounted on diagnostic instrument manipulators have been commissioned to take measurements during physics experiments.




A series of experiments planned for NIF will help scientists answer questions about the structure of Jupiter. NIF will be able to re-create the dense conditions inside Jupiter.

gamma rays, and other phenomena important for the Stockpile Stewardship Program.

## Expectations Are High

Well before 2008 and completion of construction, experiments on NIF will make significant contributions to stockpile stewardship, fusion energy, and basic science.

NIF Programs Associate Director George Miller has noted that big facilities are seldom known for the thing that they were originally designed to do. As people learn to use the facility, they come up with ideas and inventions that were never conceived of by those who designed it.

Lawrence Livermore Director Emeritus Dr. Edward Teller provides further wisdom on NIF's future. He is absolutely certain that we cannot know now what NIF will accomplish because "the greatest scientific achievements are not expected."

*—Katie Walter*

Key Words: control system, inertial confinement fusion, KDP (potassium dihydrogen phosphate) crystals, line replaceable units (LRUs), National Ignition Facility (NIF), neodymium-doped phosphate laser glass, plasma electrode Pockels cell (PEPC), Stockpile Stewardship Program, systems engineering.

***For further information contact Ed Moses (925) 423-9624 (moses1@llnl.gov).***

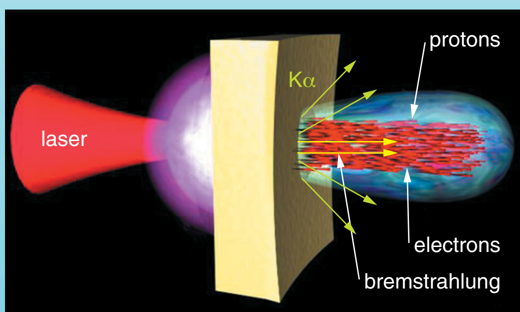
## NIF Into the Future

Laboratory scientists are working independently of the NIF project to find ways to increase NIF's flexibility and improve its experimental capabilities in the future.

Researchers at the Laboratory are exploring how to operate NIF's lasers at two colors instead of one, allowing even higher energies and longer pulse lengths. Larry Suter, winner of the 2003 Edward Teller Award for his contributions to inertial confinement fusion research, has proposed that a high-energy green laser system could provide more robust and higher-gain ignition. Studies have shown that these conditions could also be advantageous for experiments on equations of state and strength of materials. Simply removing one of the crystals in the final optics and changing the focusing lens allows a single beamline or even all beamlines to operate as green instead of ultraviolet. A quad of NIF beamlines will be available for experiments designed to study these options in the next two years.

Another goal of current research is to explore the benefits for some NIF beamlines to function as petawatt lasers. The pulse of an extremely high-power petawatt laser lasts for just a few trillionths of a second—a thousand times shorter than NIF's usual pulses—to deliver highly intense light onto targets. (See *S&TR*, October 2001, pp. 13–15.) With a modification to the master oscillator and a change to the final optics, individual NIF beamlines can operate as petawatt lasers that will allow experimentalists both to improve the high-energy and high-intensity backlighting for experiments and to explore physics processes not accessible with the baseline NIF system. The ability to generate a high-energy petawatt laser will revolutionize NIF's already unparalleled scientific capabilities.

"NIF has been designed to be a platform for cutting-edge science in the decades ahead," says Moses. "NIF's flexible beamline architecture and plug-and-play LRU configuration ensure that NIF can continually respond to the needs of the experimental community, serving us today and the young scientists of tomorrow."




A high-energy, short-pulse petawatt laser will act as a novel source of hard x rays, electrons, and protons that can be used for radiography and heating of matter.

UCRL-ID-155302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